VULNERABILITIES OF THE GLOBAL POSITIONING SYSTEM AND THE IMPACT ON THE IRON TRIAD: THE AWACS, JSTARS, AND RIVET JOINT FLEETS

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ABSTRACT

VULNERABILITIES OF THE GLOBAL POSITIONING SYSTEM AND THE IMPACT ON THE IRON TRIAD: THE AWACS, JSTARS, AND RIVET JOINT FLEETS, by Major Mark J. Walske, 84 pages.

Although there are credible threats to the United States Global Positioning System (GPS), sustainment of the constellation remains the greatest challenge. As GPS satellites reach the end of their operational life cycle, there is a risk the United States Air Force (USAF) cannot build and launch replacements quickly enough to maintain a fully-operational, 24-satellite constellation. Yet GPS is critical to infrastructure throughout the world, in particular aviation. To safely accommodate more aircraft in optimized airspace, international organizations responsible for air safety have established new navigation performance requirements. Programs to modernize military aircraft to meet these requirements rely heavily on GPS, much as civil aircraft do. This thesis analyzes the risk of overreliance on GPS by the core of the USAF command and control, intelligence, surveillance, and reconnaissance aircraft: AWACS, JSTARS, and Rivet Joint. The sensors on board these military aircraft require precision position information to effectively perform their missions. However, these aircraft may operate in a GPS denial environment. Backup navigation sources must be available for crews to carry out their missions.

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Without each of these individuals' support, I would not have been able to complete such an extensive body of work. Thank you.

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ACRONYMS

ACW	Air Control Wing
ASAT	Anti-Satellite
ATM	Air Traffic Management
AWACS	Airborne Warning and Control System
C2ISR	Command and Control, Intelligence, Surveillance, and Reconnaissance
CNS	Communication, Navigation, and Surveillance
DC2BM	Dynamic Command and Control Battle Management
DGPS	Differential GPS
DMS	Diminishing Manufacturing Sources
DoD	Department of Defense
DoT	Department of Transportation
DRAGON	DMS Replacement of Avionics for Global Operations and Navigation
ELSG	Electronic Systems Group
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
GAO	Government Accountability Office
GBAS	Ground Based Augmentation System
GLS	GNSS Landing System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
INU	Inertial Navigation Unit
IRU	Inertial Reference Unit

JFACC	Joint Forces Air Component Commander
JSTARS	Joint Surveillance and Targeting Attack Radar System
LAAS	Local Area Augmentation System
MMR	Multi-Mode Receiver
NATO	North Atlantic Treaty Organization
PM	Program Manager
RNAV	Area Navigation
RNP	Required Navigational Performance
SA	Selective Availability
SAC	Strategic Air Command
SBAS	Space Based Augmentation System
US	United States
USAF	United States Air Force
USCG	United States Coast Guard
WAAS	Wide Area Augmentation System

ILLUSTRATIONS

CHAPTER 1

INTRODUCTION

North Korean coast, October 2017--“Snoop 31,” an RC-135V/W Rivet Joint, began its turn south at the end of yet another surveillance orbit. The North Korea government had announced its intention to test a new intercontinental ballistic missile, claiming it was capable of reaching the west coast of the United States (US). Following the announcement, multilateral talks were suspended and tensions mounted. Sent to monitor the test, the Rivet Joint had positioned itself just outside the internationally recognized sovereign airspace, twelve miles off the North Korean coast. Halfway through the turn, the autopilot disengaged, flattening out the turn and pointing the nose of the aircraft toward the peninsula. The pilot immediately took control of the aircraft and flew it back to the center-of-track indicator on the large navigational display of the newly installed glass cockpit. The upgraded avionics inside the fifty-year-old airframe were some of the most modern the United States Air Force (USAF) had ever put into a reconnaissance aircraft. The large, four-engine airframe now capitalized on the same technology that guided its passenger carrying counterparts in commercial aviation.

After re-engaging the autopilot, the co-pilot noticed the coastline now seemed a bit clearer. Checking the instruments again, he assumed it was merely the illusion from the rising sun evaporating the morning fog that had been shrouding the rocky shore. The new navigation system, heavily reliant on the US Global Positioning System (GPS) for its precision position capability, showed them on course and safely in international airspace. At the end of the next leg, the aircraft again entered a banking turn. This time, just as the Korean coast disappeared from view, the copilot noticed a glint of light out the right side window. Suddenly, the radios crackled to life. “Snoop 31, Cowboy, popup two bandits seven miles, one-six-zero intercept course, flight level two-two-zero and climbing, fast!” As the co-pilot reached to respond to the air battle manager in the watching E-3 Sentry, his pilot shouted, “Verify our position, then ask Cowboy how close they show us to the coast, we may be in big trouble!” Suddenly, the dark gray form of a North Korean MiG-29 blotted out the morning sunlight streaming in through the cockpit windshield. The pilot, amid a stream of expletives, jerked the aircraft up and to the left to avoid the crossing fighter. While immediately avoiding the collision, the maneuver once again turned the Rivet Joint back toward the peninsula. Suddenly, the copilot realized it was no trick of the sun. They had crossed well into North Korean territory. The Rivet Joint was close enough to see the runways of the North Korean air base positioned on the coast. In spite of what the course indicator had told him, they were definitely not in the safety of international airspace.

Although this may read like the opening scene of a modern novel, a scenario like this could be shockingly real. US military aircraft, and most of the world’s aviation industry, has come to rely almost exclusively on GPS for the precision navigational and timing requirements of flight. The organizations responsible for regulating flight safety have outlined requirements for navigation to a precision that only GPS can currently meet. However, GPS is not a perfect system. Like many technologically driven forms of automation, it is susceptible to errors and even failure. The current system is old and has been operating well beyond its designed life expectancy. As an open-access technology, it also remains vulnerable to denial and direct attack by America’s adversaries. The global unrestricted availability granted by the US, the sharing of technology, and our partnerships in developing the next generation of Global Navigation Satellite Systems (GNSS) may give those that would do America ill an opportunity to turn one of our greatest military assets against us or deny US forces its uses as it seeks to gain and maintain air and space superiority.

Although a potential external threat is cause for concern, the greatest threat to GPS may actually come from within. The current set of GPS replacement satellites faced numerous delays in development and launch because of shifting requirements and inadequate contract execution. The USAF states it will incorporate lessons learned from these issues, yet it continues with an aggressive and optimistic schedule for the next generation of GPS satellites. If development and deployment of these new satellites is delayed, the US faces the real possibility that the GPS constellation will not have enough operating satellites to provide full operational service coverage.[1]

Despite various threats to system integrity, civil aviation still considers GPS the primary source to meet navigation performance requirements in increasingly congested airspace throughout the world. International agencies charged with ensuring air safety feel the high level of accuracy GPS provides is the only way to accommodate so many aircraft in such high use airspace. Since many of the USAF's larger aircraft routinely transit these same air routes, they must also comply with both US and international standards of performance. However, these aircraft also operate in GPS denied environments and must have additional navigation options to continue to execute their primary missions safely.

Current USAF modernization programs, especially the Command and Control, Intelligence, Surveillance, and Reconnaissance (C2ISR) fleet, look to replace obsolete and inadequate components with new modernized avionics suites that rely too heavily on GPS for precision navigation and timing. Some of these modernization programs focus on replacing the navigator with modern technology as a cost-savings measure. Most have already faced budget cuts causing reductions in the amount and type of equipment being replaced or significant delays in development and implementation. At a time of ever tightening budgets and scrutiny of every defense dollar spent, the USAF may have unintentionally accepted too great a risk with its overreliance on a man-made navigation constellation dependent on good luck and good will.

Background

The Global Positioning System

Since the dawn of man's long-range expeditions, explorers realized the importance of precision timing coupled with triangulated fixes to accurately calculate their terrestrial positions. The concept of navigating off celestial bodies is not new. As early as the 1700s, mariners were navigating with octants, and later sextants, to fix their positions off the sun, moon, and stars. When coupled with the precision of marine chronometers, old world navigators calculated a ship's position accurately enough to explore the vast expanses of the oceans.[2] Unfortunately, these optically measured orbital bodies were not always visible.

With the advance of radio technology, sailors and early fliers turned to land-based, man-made radio beacons to calculate position information. Beacons too had limitations and often proved unreliable, especially when the aircraft or ship was out of signal range.

It was not until the launch of the first satellite that scientists discovered they could monitor reliable radio signals from space to calculate an exact position on the earth.[3] In the post-Sputnik era, the US had committed itself to space superiority and the race was on to exploit its uses. As part of the overall space strategy, the US looked to better answer the challenges of long-range navigation. The 1960s saw the proliferation of space-borne projects that included initiatives from a global communications capability to high-speed travel. However, not all of these projects were sustainable or even practical. One project that endured was the US Navy's fledgling satellite navigation program. Transit, developed in partnership with Johns Hopkins Applied Physics Laboratory, was the US's first successful attempt at a space-based navigation system.

The US Navy originally developed Transit to assist in locating ballistic missile submarines and other Navy vessels. However, the satellites had a number of drawbacks. First, they were only capable of two-dimensional position information; they only provided latitude and longitude. This was not a significant problem for surface vessels, but an issue for anything above sea level. Secondly, Transit users had to account for their velocities to calculate positions properly, making it mostly unusable by aircraft. Other issues included limited satellite coverage and long lock-on times to acquire the navigation signals. The Navy's follow-on program, Timation, attempted to correct for some of these shortcomings and added a new feature to the navigation service, precision timing. The Timation satellites were the first to carry atomic clocks. These precision chronometers allowed for better satellite position prediction and lengthened the time between required updates by ground control stations.[4]

At the same time, the USAF was working on a satellite navigation program of its own. A program designated System 621B introduced reliable three-dimensional navigation capable of providing continuous latitude, longitude and altitude information. Additionally, the Air Force's system demonstrated the ability to transmit multiple signals on a single frequency by using pseudorandom noise to differentiate the satellites transmitting them. However, the System 621B never reached full development due to the other services pursuing similar projects and competing for the same development funds.[5]

In an effort to capitalize on the break-though work done by each of the different programs, the Department of Defense (DoD) created a joint committee to oversee all satellite navigation initiatives. The Navigation Satellite Executive Group (NAVSEG) outlined the specifications and performance of a single satellite navigation constellation. In 1973, the Air Force was designated the lead service to develop and operate this new system. Combining the signal structures and frequencies of System 621B, the satellite technology and orbit geometry of Timation, and the use of atomic clocks for precision timing proposed by both programs, NAVSEG created the Navigation Signal, Timing, and Ranging Global Positioning System, NAVSTAR GPS.[6]

Since the launch of the first two prototypes, re-designated and redesigned Timation satellites, there have been eleven Block I, twenty-eight Block II and Block IIA, and twenty Block IIR and Block IIR-M satellites launched in a continuous effort to sustain, modernize, and secure the NAVSTAR GPS constellation.[7] The next generation of GPS satellites, Block IIF, is nearing launch and the contract for development and production of the Block III satellites has been awarded. But GPS is not the only program being modernized.

Modernizing the Fleet

Occasionally, a seemingly simple question opens a vast labyrinth of complications, estimated effects, and, inadvertently, a problem creating more questions than answers. One such simple question, asked at a routine working-group meeting, continues to be a topic of discussion in the 552d Air Control Wing (ACW), the 551st Electronic Systems Group (ELSG), and Air Combat Command. The impact of its elusive answer may ripple through the Air Force once the many secondary questions are resolved: “Are we going to remove the navigator position from the flight deck of the E-3?”

The question surfaced while trying to define contractual requirements for the DMS (Diminishing Manufacturing Sources) Replacement of Avionics for Global Operation and Navigation (DRAGON) program. However, the question marks the trend of larger military aircraft reducing their flight crews and relying more heavily on upgraded avionics, digital technologies, and GPS for navigation. Although the Federal Aviation Administration (FAA) has declared GPS to be the primary navigation source to grant aircraft access to the National Airspace Structure (NAS), the organization acknowledges GPS is fallible and requires a ground navigation aid backup system for civil air traffic.[8]

Military aircraft, however, have much more stringent requirements. Not only do military aircraft have to comply with FAA and international flight standards, C2ISR aircraft are required to perform their missions in close proximity to the sovereign airspace of potentially hostile nations. Their navigation systems must provide precision guidance to prevent crossing into unfriendly airspace and are the primary source of positioning and timing for their onboard mission and networking equipment. DRAGON is a joint program to modernize the cockpit avionics of both the US and North Atlantic Treaty Organization (NATO) E-3 Airborne Warning and Control System (AWACS) aircraft. Nonetheless, DRAGON is not the first program to modernize the cockpit of a large USAF aircraft.

As early as 1987, Strategic Air Command (SAC) initiated a study into reducing the number of aircrew in the KC-135 Stratotanker aerial refueling aircraft.[9] Initially, SAC conducted this study to explore modernization of the older avionics originally built into the tanker fleet and to capitalize on the then-emerging aviation technologies. After the fall of the Berlin Wall and the end of the Cold War, the United States hoped to significantly reduce its standing military force and make the most of the diminished threat. Defense spending to counter the former Soviet Union's military build-up was no longer required. The DoD shelved or simply cut many programs outright with the menace of the "Evil Empire" abated.

In order to comply with the DoD mandated drawdown of forces in the 1990s, the Air Force hoped to reduce its overall force strength while continuing to meet its operational missions. The Air Force Personnel Center aimed to reduce total manning and used the aircraft modernization studies as a basis to identify excessive, redundant, or obsolete positions.[10] Aviation technology advanced by integrating faster, cheaper, and smaller computer and digital hardware into avionics suites. During the Gulf War, GPS proved viable as a navigation aid for both ground and air forces. Avionics companies had already begun developing integrated receivers for aerial navigation. The advances in commercial aviation technology promised to increase automation and reduce overall aircrew workload. The Air Force believed these emerging technologies would allow changes to the composition and function of its flight crews, trading manpower for equipment. By upgrading the avionics in its aging KC-135 Stratotanker aerial refueling aircraft, SAC believed they could remove the navigator position from the tanker flight crew and reduce the total Air Force manning.

The modernization program, called Pacer CRAG (Compass, Radar, And GPS), updated the KC-135 avionics. Other multi-crew aircraft in the Air Force inventory had operated without navigators. Nevertheless, this was the first modernization program to purposefully remove the navigator from the flight crew. The US military has begun designing many of its other aircraft without a flight deck position for the navigator. These include the C-17 Globemaster III and the C-130J Hercules. It has caused Air Force leaders to question the overall need for navigators on multi-crew aircraft.[11] However, there have been few detailed studies on the necessity of navigators given the growing reliance on GPS and other advances in navigation and air traffic management. Recent world events have proven that should potentially hostile nations wish to deny America use of this technology; they now have sufficient means to do so. Both denial and destruction of modern navigational systems are now real threats to air superiority.

The E-3 AWACS, a cold-war era airborne early-warning radar system, now provides combatant commanders with more than just a bird's eye view of the battlefield. Repurposed as a battlefield command and control platform, it has become a critical node in information superiority on the battlefield and in the skies above. AWACS, along with the Joint Surveillance Targeting Attack Radar System (JSTARS) and the entire RC-135 fleet, most commonly referred to as Rivet Joint, comprise the USAF's "Iron Triad," the three airborne elements of Dynamic Command and Control Battle Management (DC2BM) critical for theater intelligence, surveillance, reconnaissance, and battle management for the Joint Forces Air Component Commander (JFACC) in an operational theater.[12]

Collectively, they are critical elements in achieving both information and air superiority for US forces. However, in order for these irreplaceable assets to remain on-station, the Air Force must modernize their avionics to comply with recent and future changes to airspace access requirements. Recently, the FAA, the European Organisation for the Safety of Air Navigation (EUROCONTROL), and the International Civil Aviation Organization (ICAO) mandated specific navigation performance requirements for access into high-use airspace. DRAGON's goal was to install new Communications, Navigation, and Surveillance (CNS) equipment to aid Air Traffic Management (ATM) in compliance with these new requirements.

The new CNS/ATM requirements are part of a modernization effort to handle the ever-increasing global air traffic. In 1983, ICAO commissioned a committee to study current aircraft avionics and traffic management infrastructure. Their report concluded these systems could not handle anticipated increases in air traffic. All indications were that the number of aircraft would increase while the available airspace to put them in would not. Limited to a finite amount of airspace, ICAO had to find a way to accommodate more aircraft safely. The answer lay in technology. To accommodate more aircraft vertically, ICAO insisted on upgraded avionics. Aircraft had become more stable in flight, leading to fewer inadvertent changes in altitude. This allowed for reduced vertical separation minima. By capitalizing on the precision of GPS, aircraft have far greater navigational accuracy. This allowed for reduced separation of aircraft along routes. Beginning as soon as 2011, all aircraft transiting North Atlantic, Pacific, and European airspace must comply with the new requirements for precision positioning, navigation, and timing. Any non-compliant aircraft will be denied access to optimal routing, significantly increasing transit time and fuel requirements.[13] Special exceptions may be made minimally equipped fighter-like military aircraft. However, more frequent users, such as military long-range cargo aircraft and larger special mission platforms, such as those of the Iron Triad, must fully comply in order to make use of these optimized, heavily congested air routes.[14]

This thesis attempts to correlate the vulnerabilities of GPS, the new CNS/ATM requirements, modernization programs to meet these requirements, and the possible impact to the mission effectiveness of Iron Triad aircraft. In order to do so, it investigates the following questions.

Primary Research Question

Will overreliance on US space-based navigation technology hinder the mission effectiveness of the Iron Triad aircraft?

Secondary Research Questions

How reliable is the US space-based navigation system; what are the threats to and vulnerabilities of GPS; and how are they currently being mitigated?

Will these risk mitigation procedures be effective for the environments in which the Iron Triad missions fly?

What are the navigation requirements of the Iron Triad aircraft and how is the USAF meeting them?

What are the current and future initiatives to upgrade or improve the navigation systems on Iron Triad aircraft?

What are the risks of modifying military aircraft to meet civil aviation standards without considering the vulnerabilities of those systems?

Assumptions

One of the primary assumptions of the DRAGON program is that the USAF will continue to fund and complete the modification on schedule. In the past, the USAF has delayed programs due to cost overruns and contractual issues. The DoD, and subsequently the USAF, is constantly scrutinizing each program and evaluating it against current and perceived future needs. As a result, initiatives that exceed original cost estimates are often delayed pending extensive reviews. For example, the program to upgrade the engines on the JSTARS fleet[15] and the C-130 Avionics Modernization Program have both been delayed.[16] However, with the pressure from ICAO and the international aviation community, it is unlikely the USAF can delay DRAGON and still meet the requirements established by the CNS/ATM initiative without losing the ability to deploy the AWACS fleet beyond US airspace.

A second assumption regarding CNS/ATM is that ICAO and the international aviation community will not grant non-compliant aircraft access into or through European and optimized trans-oceanic airspace. As an additional assumption, EUROCONTROL and ICAO may grant accommodation for US forces access in the event of major combat operations around the world. But, these accommodations have not always been made in the past. For example, France did not allow US fighter aircraft into their airspace during Operation El Dorado Canyon and Turkey did not allow operations from their territory during Operation Iraqi Freedom. Countries may soon use CNS/ATM requirements as leverage for their political agendas. The DoD cannot expect special treatment for contingency operations and will have to comply with CNS/ATM mandates in order to rotate aircraft through routine air traffic routes into and out of theater.

Definition of Key Terms

The term commonly used to refer to any form of satellite navigation structure is Global Navigation Satellite System or GNSS regardless of ownership by any individual nation or organization. This thesis refers to the US GNSS, the NAVSTAR Global Positioning System, simply as GPS. Other GNSS go to by names such as the European Space Agency's Galileo, Russia's GLONASS, and others. Additionally, when referring to a generic GNSS or a specified system, the term usually addresses the three main elements of a GNSS collectively: the space vehicles or satellites; the ground control segment and associated hardware and software; and the user equipment, commonly called receivers.[17]

The FAA, EUROCONTROL, and ICAO use the terms optimized routing or optimized airspace refer to tightly controlled, heavily used airspace and air traffic routes such as the North Atlantic Tracks, Pacific Tracks, and the majority of airspace over the European continent. This airspace is the target of the CNS/ATM initiatives as demand for its use by commercial air traffic increases.

The term overreliance refers to the emphasis the CNS/ATM initiative places on using GNSS to meet precision navigation requirements. Additionally, it refers to the extensive use of GPS to provide precision navigation information for military aircraft.

Unfortunately, there is no single, clear-cut definition of mission effectiveness. One previous study defined mission effectiveness as strictly dealing with a high-threat combat environment. This definition is too specific for Iron Triad missions. However, some of the elements used to further describe mission effectiveness may be used. For the purpose of this thesis, mission effectiveness refers to the ability of an aircraft to perform its primary mission with little or no degradation.[18] The aircraft must also be able to continue to meet flight safety standards as well as operate safely in transit to, from, and within its mission airspace.

Limitations

This study is unclassified. No "For Official Use" information was used. This limited the scope and depth of the topics and restrained discussion details.

Additionally, some of the more technical data on the cockpit upgrades is proprietary information. It is the intellectual property of the contracted aviation companies. None of this information was used. This also limits the scope and depth of detail in describing the exact program specifications.

Finally, there are many journal and magazine articles, published reports to various governmental agencies, and academic research papers that all debate various points on GPS. However, there are very few books published on the topic. Those that do exist are more than a decade old, but provide insight on the history of GPS. The research for this paper focused on the most recent and timely material available since the modernization programs on the fleet of Iron Triad aircraft and other USAF platforms are progressing daily.

Delimitations

This thesis focuses only on the impact of potential GPS degradation on Iron Triad aircraft. It does not discuss other GPS uses such as major infrastructure and economic sectors including telecommunications, electrical power distribution, banking and finance, transportation, environmental and natural resource management, agriculture, and emergency services.[19] The implications of that level of impact reach far beyond the scope of this thesis. Additionally, the focus will be on Iron Triad aircraft as central nodes in the C2ISR capabilities for combatant commanders. Specifically, this paper will often focus on just the DRAGON program and the E-3, as it is the most current and advanced cockpit modernization program of any of the Triad aircraft. Members of the 551st ELSG, responsible for upgrade initiatives for both AWACS and JSTARS airframes, consider the DRAGON program a model to modernize other Triad aircraft to comply with CNS/ATM requirements. It provides the best context in which to discuss USAF upgrade efforts for the large airframe fleet.

Navigators perform many additional tasks throughout the Air Force that fall outside of mission planning or cockpit duties. Navigators fill staff positions from the Joint Staff down to the operational level in line squadrons. The USAF has conducted manpower studies reviewing the total officer force requirements as well as the need for rated expertise in key specialized billets. This thesis, however, will not address any of the personnel requirements of staff or command or attempt to address overall USAF manning.

Significance of the Study

This research study will potentially impact ongoing USAF modernization programs. The primary focus of these programs is to bring USAF aircraft into compliance with CNS/ATM requirements. But CNS/ATM requirements emphasize the use of GPS and its augmentation systems for precision navigation. Numerous studies, articles, and reports discuss the implications of a GPS failure or outage to the civil sector. However, limited data directly ties the impact of GPS vulnerabilities to the mission effectiveness of USAF aircraft. Most studies focus on the dangers of GPS denial to ground forces. This study highlights the risks of military aircraft modified to meet civil standards of aviation heavily reliant on GPS without considering the vulnerabilities of those systems.

About the Author

The author is uniquely qualified to discuss this research thesis in that he is both a subject matter expert on the DRAGON modernization program, including the CNS/ATM requirements driving it, and has over ten years experience as a USAF navigator. He retains the qualification rating of Evaluator/Instructor Navigator on the E-3 Sentry, AWACS, and has over 2,500 flight hours. He was one of the last navigator students trained in celestial navigation and the use of a sextant as the USAF transitioned to heavier reliance on GPS as a primary source for aircraft navigation.

The author's most recent assignment was as the 552d ACW Chief of Flight Deck Requirements in the Plans and Requirements Branch and the Wing Program Manager for the DRAGON modernization program. He has firsthand knowledge of the efforts to modernize aging USAF airframes and the navigational requirements of the Iron Triad fleet. He has been involved in the evaluation of the navigator's role for the DRAGON program and the potential risks of overreliance on technology for these critical airframes.

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[13]Alexander Alshtein et al., "Mission Effectiveness and European Airspace: US Air Force CNS/ATM Planning for Future Years," *The Journal of Defense Modeling and Simulation* 4, no. 2 (2007): 1. http://www.dodccrp.org/events/11th_ICCRTS/html/papers/139.pdf (accessed 12 May 2010).

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[15]Patty Welsh, "Joint STARS Resumes Re-engining Program with Two Major Contract Actions," GlobalSecurity.org, http://www.globalsecurity.org/military/library/news/2010/03/mil-100318-afns09.htm (accessed 22 May 2010).

[16]Amy Butler, "USAF Mulls Retiring Old C-5s, Backs C-130 AMP," Aviationweek.com, 12 April 2010, http://www.aviationweek.com/aw/generic/story_generic.jsp?channel=aerospacedaily&id=news/asd/2010/04/12/12.xml (accessed 22 May 2010).

[17]United States Government Accountability Office, *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities* (Washington, DC: Government Printing Office, 2009), 1.

[18]William K. Starr and Donald A. Welch, "A Study of Pilot Attitudes Regarding the Impact on Mission Effectiveness of Using New Cockpit Automation Technologies to Replace the Navigator/Weapon System Officer/Electronic Warfare Officer" (Master's Thesis, Air Force Institute of Technology, 1991), 1-6.

[19]United States Government Accountability Office, *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities* (Washington, DC: Government Printing Office, 2009), 4.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses significant literature used in the research of this thesis, briefly analyzes the major sources of information, and relates the relevance of this thesis to the existing body of work. There is extensive documentation detailing the integration of GPS into nearly every aspect of commerce, banking, transportation, communication, and major segments of the US’s critical infrastructure. Some of the literature provides a historical background on the beginnings and evolution of the GPS constellation and its future upgrades and capabilities. News articles and governmental studies alike focus on the threats to and vulnerabilities of GPS and their potential impact on the civil infrastructure that rely so extensively on it. Much of the concern regarding the loss of GPS for aviation focuses on the impact to civil aircraft. Many of the studies discuss augmentation systems to provide a level of redundancy. Only a few reference the impact of GPS degradation to all military uses. Researchers undoubtedly feel the greater risk of degradation is to the civil sector as the military uses two GPS frequencies for precision position versus a single civil frequency. Only the federally commissioned reports discuss the military’s reliance on GPS for aviation in depth. The various governmental departments directed researchers of these studies to consider impact to all users of GPS including civil infrastructure, commerce, transportation, and military. Various news and trade websites provided cursory information on GPS impacts to military aviation.

Some obvious correlation exists between commercial and military aviation, specifically in regards to CNS/ATM mandates that all aircraft must comply with in order to gain access to restricted airspace. Information on those requirements is readily available from ICAO and FAA websites. Unfortunately, little research and no significant literature have linked GPS vulnerabilities to CNS/ATM mandates. No unclassified studies have been conducted gauging the ability of USAF aircraft to accomplish their missions should GPS falter.

Significant Literature

The USAF is responsible for the sustainment and acquisition of new technologies to modernize the GPS constellation. The current satellite development program, known as GPS Block IIF, has had trouble with rising program costs and significant production and deployment delays.[1] As a result, Congress requested the Government Accountability Office (GAO) to conduct a study on the challenges of GPS sustainment and upgrade. The GAO study identified one of the most significant future GPS vulnerabilities, replacement satellites. This vulnerability constitutes one of the key concerns for this thesis.

Commissioned Government Studies

Two key government reports serve as primary sources associated with GPS vulnerabilities. The first, presented to the Department of Transportation (DoT) in August 2001, is referenced in nearly every other document discussing the threats to GPS. The John A. Volpe National Transportation Systems Center produced *The Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System,* more commonly known as “The Volpe Report.” Most experts consider the Volpe Report to be the most comprehensive document regarding GPS threats. The *Report of the Commission to Address United States National Security Space Management and Organization*, also known as “the Rumsfeld Report,” is the other critical GPS study. Both documents address nearly every possible threat to the GPS Operational System in detail. Although both were published nearly a decade ago, they both remain relevant to today's threats to GPS. However, neither document discusses modernization, sustainability, or replacement of the GPS satellites, ground control components, or user equipment.

The GAO study, *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities* is the most significant recent work on GPS vulnerabilities. Published in 2009, it takes a hard look at the USAF acquisition strategy for the next generation GPS satellites, the Block IIIA. The report identified replacement and sustainment as the most credible threat to the GPS constellation. The study analyzed the execution of the previous satellite replacement program, the Block IIF. Although the USAF believes it will be able to deliver the new satellites on time, the GAO study, through analysis of the entire program, identified numerous issues that put the scheduled timeline at risk.[2] Should launch of the new satellites be delayed, the US faces the real possibility that it will be unable to sustain a fully operational, 24-satellite constellation.

The orbiting satellites that make up the current constellation will reach the end of their operational life faster than they can be replaced.[3] For military users, the security capabilities of the new M-Code will not reach full operational capability until 18 satellites are broadcasting. Currently, only the eight GPS Block IIR-M satellites launched between September 2005 and August 2009 can transmit the new code.[4] All of the GPS Block IIF satellites will transmit the M-Code. However, even if the satellites are deployed on schedule, the military users may not be able to capitalize on future security measures as there will not be enough receivers produced and installed in military aircraft. The study highlighted significant delays in the development and production of the necessary user equipment needed to receive and use the new code.[5] This thesis will discuss the status of the GPS constellation and user receivers in more detail.

Service School Research

Two Master's theses discussed the removal of the navigator position from the flight crew of the KC-135 because of the Pacer CRAG cockpit modification program. Both of these highlighted mission effectiveness in the exchange of manpower for technology. The *Analysis of the KC-135 Three-Person Cockpit* identified the main concern among National Guard tanker units was task saturation in a wartime environment.[6] The *Study of Pilot Attitudes Regarding the Impact on Mission Effectiveness of Using New Cockpit Automation Technologies to Replace the Navigator/Weapons System Officer/Electronic Warfare Officer* concluded pilots of USAF aircraft did not believe it was possible to effectively replace navigators with technology while performing high-threat combat missions, especially if that technology was not working correctly.[7]

For Want of a Nail: An Assessment of Global Positioning System Satellite Replenishment provided GPS historical information and complemented the GAO study on sustainability. It primarily addressed the USAF approach to launch replacement satellites and only briefly discussed the impact of GPS degradation on military aircraft. *The Walker Papers*, a published work from Air University Press, provided additional detail on GPS history and GNSS and augmentation efforts by other nations. Finally, a student text from the US Army Command and General Staff College thoroughly summarized the GPS vulnerabilities of the space environment.

Other sources

The Journal of Defense Modeling and Simulation article provided substantial information on CNS/ATM requirements and the impact of non-compliance to US military aircraft. Although it focused primarily on fighter aircraft, its conclusions can be applied to the entire USAF fleet. A significant number of on-line news articles and organizational websites rounded out the details and provided a significant amount of background material on GPS, the CNS/ATM initiatives, and the Iron Triad. The Stanford University, USAF, and official GPS websites provided details on the GPS history. The FAA website provided in-depth information on the various augmentation systems to GPS. The ICAO and Armed Forces Communications and Electronics Association (AFCEA) websites detailed requirements of the CNS/ATM mandate. Finally, the US Naval Observatory provided extensive information on the current status and composition of the GPS constellation.

Analysis of the Literature

Research conducted on the vulnerabilities of GPS is extensive and thorough. The research covers nearly every possibility from the improbable to the frighteningly possible. This thesis only used information directly affecting GPS use by aircraft. It did not use evidence discussing jamming and spoofing as it pertained to ground maneuver units, infrastructure, or commerce. However, this thesis does consider investigations into GPS vulnerabilities and civil aviation. Documentation discussing the forthcoming CNS/ATM requirements does address some of these vulnerabilities and the use of GPS augmentation to accommodate commercial air traffic should GPS become degraded. Only the GAO study on sustainability discusses the loss of full operational capability of the GPS constellation. However, it does not correlate its impact to GPS users. It is likely the extent of the impact would far exceed the scope of the GAO study. None of the research addresses the futility of an augmentation system should there be no GPS signal to correct. The monograph on satellite replenishment is the only current document to addresses the impact to mission effectiveness of military aircraft should GPS be compromised. Some of the studies detail technology to overcome jamming and spoofing of the GPS signal. But again, these technologies would not matter if there is no GPS signal available. One FAA study does discuss potential backup navigation sources should GPS be degraded. However, the study identifies that the majority of these systems would be for approach and landing at airports. The systems identified for long-range navigation are only in experimental development stage.

Additional governmental reports provided background on the KC-135 modernization program, dynamic operations of the Iron Triad fleet, supplemental information on CNS/ATM, and the history of GPS.

Significance of the Thesis to the Existing Literature

This thesis identifies the threats to and vulnerabilities of the GPS operational system and assesses their impact on Iron Triad mission effectiveness. It bridges the gap between the vulnerabilities of GPS sustainment and military aircraft modernization programs that rely heavily on GPS. It identifies the need for reliable backup navigation sources for Iron Triad aircraft and their sensor equipment in order to fulfill their missions. Current modernization programs aimed at achieving compliance with CNS/ATM requirements for access into heavily regulated optimized airspace focus on the use of GPS for precision navigation. The strict CNS/ATM requirements drive the reliance on

GNSS as the only navigation source capable of such a high level of precision. However, aircraft such as those of the Iron Triad operate near hostile borders where some of the potential threats to GPS reliability may indeed become a reality. Should the modernization efforts place too much emphasis on GPS and not provide an adequate redundant navigation source, the aircraft of the Iron Triad may be forced to position their sensors farther from the battle space in order to retain adequate GPS signal strength and lose critical coverage or perhaps abandon their mission altogether. Such actions would result in the loss of detection of invaluable battlefield information vital to protection of US air and ground forces.

In summary, there is an extensive body of research on the potential dangers to the GPS constellation. There are many sources available on the requirements for aircraft access into high-traffic airspace. However, the lack of documentation on redundant navigation considerations for military aircraft, specifically in the modernization programs of USAF DC2BM aircraft, was a key concern of this literature review.

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[1]United States Government Accountability Office, *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities* (Washington, DC: Government Printing Office, 2009), 1-2.

[2]Ibid., 17.

[3]Ibid., 19.

[4]United States Naval Observatory, "Current GPS Constellation, Block II Satellite Information," ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt (accessed 23 May 2010).

[5]United States Government Accountability Office, *Global Positioning System*, 28.

[6]Robert A. Deivert, "An Analysis of the KC-135 Three-Person Cockpit" (Master's Thesis, Air Force Institute of Technology, 1994), 5-2.

[7]William K. Starr and Donald A. Welch, “A Study of Pilot Attitudes Regarding the Impact on Mission Effectiveness of Using New Cockpit Automation Technologies to Replace the Navigator/Weapon System Officer/Electronic Warfare Officer” (Master’s Thesis, Air Force Institute of Technology, 1991), 5-34.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter discusses the research methods used in gathering information for this thesis. It briefly discusses the resources used to obtain the information, the actual methodology used, and the strengths and weaknesses of the research.

Available Information

The Combined Arms Research Library at Fort Leavenworth, Kansas provided the majority of the journal articles, government reports, and monographs on the history of GPS. FAA and ICAO websites as well as detailed knowledge of the topic from previous experience provided much of the information on CNS/ATM requirements. Finally, information on the Iron Triad and the modernization programs underway was mostly from eighteen months of working with various government contractors, aviation companies, and Air Force personnel and direct involvement in the DRAGON program. Additional unclassified websites such as the US Naval Observatory, Garmin, and the National Aeronautics and Space Administration provided supporting information to fill in any knowledge gaps.

Research Methodology

This thesis relied on primary and secondary sources of information to answer the primary and secondary research questions. The source material was separated along common topic areas: GPS, CNS/ATM requirements, and information on the Iron Triad. This was further broken down into subcategories. GPS information was separated into historical reference, overall system vulnerabilities, and issues that specifically addressed the military aviation community. For CNS/ATM requirements, the information mostly focused on the upgrades that all aircraft, including military aircraft, must have in order to access domestic and international optimized airspace. Finally, information on the Iron Triad primarily focused on the DRAGON modernization program of the E-3 Sentry. The DRAGON program is the most recent and most extensive modernization program of the Iron Triad aircraft. It has already addressed numerous modernization challenges in mating new digital technology to aircraft originally built with an analog avionics suite. Additionally, the focus of the DRAGON program is to meet all current and future CNS/ATM requirements with a single modification. Research on modifications to the other Iron Triad aircraft reveals further modification will be necessary to meet future CNS/ATM requirements. In addition to documentation and slide presentations, various members of the USAF 551st ELSG System Program Office, the 552d ACW Requirements Office, and Boeing Integrated Defense Systems program engineers provided unattributed statements during program meetings. These statements were recorded in the author's personal notes. To avoid privacy violations, all personal identifying data has been removed from the remarks. No proprietary material was used to avoid copyright infringements.

The thesis used limited quantitative data as there was little in the way of actual experimental research. One study compared the cost of GPS equipment and its upkeep to the cost of training and retaining navigators. The thesis makes only reference to the cost savings analysis. Additional research on the probability of maintaining the GPS constellation provided significant evidence of potential GPS unavailability. The majority of the remaining information used was qualitative in nature. This detailed information was then gathered and collated to paint a bigger picture of potential issues in the future with the overreliance on GPS for the future upgrades of the Iron Triad fleet.

Strengths and Weaknesses of the Methodology

One of the strengths of this methodology is that the majority of the data on the vulnerabilities of GPS comes from multiple sources. These studies generally agree and their conclusions support one another.

All the major research studies used were the objective work of government and independent research organizations. The thesis obtained additional information from the most primary sources available, such as CNS/ATM information from FAA and ICAO websites and GPS satellite status information from the US Naval Observatory.

The major studies on GPS vulnerabilities and sustainment spanned an extended period. They were the results of years of research and in-depth analysis by system experts from a cross section of commercial and governmental agencies. Each of the commissioning agencies has a stake in the health and reliability of the GPS constellation.

One of the weaknesses of this methodology is that much of the information gathered on the vulnerabilities of GPS focuses on the impact to civil users. There is little open source information on the impact to military users and military aviation. This is most likely because civil users of GPS vastly outnumber military users. The limitation of only unclassified material hampered the research. A few persuasive “For Official Use Only” documents are referenced in only the broadest sense. Unfortunately, the impact of their data is diluted. As a result, the bulk of research focuses on the impact to the commercial and transportation sectors and is correlated to military applications.

Finally, some of the research was dated. Both the *Analysis of the KC-135 Three-Person Cockpit* and the *Study of Pilot Attitudes Regarding the Impact on Mission Effectiveness of Using New Cockpit Automation Technologies to Replace the Navigator/Weapon System Officer/Electronic Warfare Officer* were written in the 1990s. Other material found on GPS and FANS spans nearly two decades. However, this data was still accurate and relevant as it provides the necessary history and background to topics discussed in the thesis.

CHAPTER 4

ANALYSIS

This chapter analyzes GPS vulnerabilities, addresses concerns regarding the overreliance on GPS in aircraft avionics modernization programs, and evaluates the impact these changes may have on the Iron Triad fleet's mission effectiveness. In order to understand the growing concern of GPS reliability more fully, this chapter details threats and vulnerabilities, explains what systems are in place or proposed to mitigate some of these risks, and evaluates how these mitigations may or may not be effective for Iron Triad aircraft.

Delays in the next generation of GPS satellites and the lack of upgraded GPS receivers available for military aircraft present the greatest risk. This analysis discusses the various augmentation systems developed to enhance GPS accuracy to better meet safety-of-flight standards.[1] Next, the study looks at navigation requirements for flight in international airspace, specifically the recent CNS/ATM requirements for access into optimized airspace across the Atlantic, Pacific, and European continent. The study also identifies Iron Triad navigation requirements and how they differ from those associated with commercial and other USAF aircraft. Finally, this chapter analyzes the current modernization efforts to bring the Iron Triad aircraft into compliance with the CNS/ATM requirements. Emphasis focuses on the DRAGON program for the E-3 AWACS as it is most recent in development, has already encountered navigation requirements issues, and considered be the model for other Iron Triad upgrades by the 551st ELSG. The research will also consider a study on past upgrades to the KC-135 aircraft. This study addresses the mission effectiveness of trading manpower for technology in a dynamic combat environment and serves as a guide for future upgrades.

The GPS Operational System

All space systems consist of three basic elements. To discuss the vulnerabilities of the GPS Operational System more clearly, it is easier to break the structure into more these common divisions. Most space systems, GPS included, consist of three major parts: the space segment or satellites, the ground control segment, and the user segment or receivers.[2] These three segments make up the primary components of the GPS Operational System. However, there is one more often overlooked component specific to GPS.

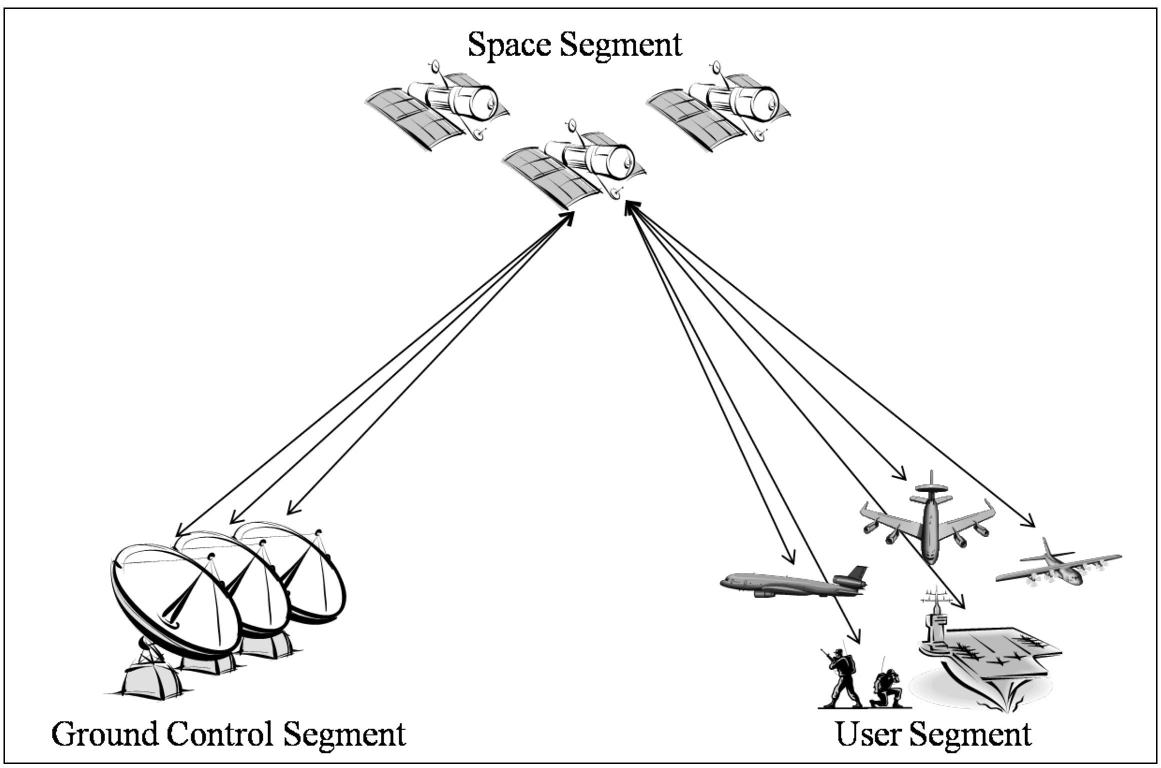

Figure 1. GPS Operational System
Source: Created by author.

GPS also uses augmentation systems to enhance its positional accuracy. All forms of GPS augmentation are referred to Differential GPS (DGPS). DGPS is further categorized as either a Space Based Augmentation System (SBAS) or a Ground Based Augmentation System (GBAS). The term DGPS also specifically refers to the United States Coast Guard (USCG) Maritime Differential GPS Service and, in some cases, other countries maritime DGPS services. The USCG created its DGPS, a GBAS, to enhance the GPS positional accuracy in and around the US coastal waters, waterways, and Great Lakes.[3] For this reason, this thesis will only discuss DGPS systems that augment the aviation uses of GPS, primarily of the US Wide Area Augmentation System (WAAS) and the Local Area Augmentation System (LAAS).

The FAA, in conjunction with the DoD and the DoT, developed WAAS to enhance GPS signals to facilitate precision aircraft approaches, known as GNSS Landing System (GLS) approaches, at US civil airports.[4] The FAA has stated the GPS position signal does not meet accuracy, integrity, and availability standards for precision approach requirements.[5] WAAS uses a series of precisely surveyed ground reference stations spread out across the continental US, Alaska, and Hawaii to receive GPS position signals and compare it to the exact known position of each station. Each of these reference stations transmits data to two wide-area master stations, one on each coast of the US. The wide-area master station corrects for the differences between the position given by the GPS signal and the known position of the reference station then transmits a corrected signal to navigation payloads onboard two geostationary communications satellites.[6] The two communications satellites continually broadcast the corrected signal over both North and South America using a GPS band frequency with a different pseudorandom code to identify it.

Even though the WAAS satellites transmit the corrected position signal beyond the coasts, they are unusable outside of North America. The ground reference stations used to improve signal accuracy are only within the Northern Hemisphere. Additional ground reference stations would need to be built and networked in order to extend the WAAS coverage. Although the critical components of WAAS are the reference and wide-area master stations are ground systems, WAAS is categorized a SBAS since the satellites broadcast the augmentation signal. Other nations have developed or are developing similar SBAS services: European Geostationary Navigation Overlay System (EGNOS), India's GPS and Geo-Augmented Navigation System (GAGAN), and Japan's Multifunction Transport Satellite (MTSAT) Satellite Augmentation System (MSAS).[7] US civil air traffic will be able to use these systems as they come online. Military aircraft could also use these signals for peacetime transit flights. However, it is doubtful that the DoD would authorize US military aircraft to use these augmentation systems during combat operations. These systems are unencrypted and susceptible to many of the same GPS signal vulnerabilities.

The FAA is still developing its primary GBAS, known as the Local Area Augmentation System (LAAS). Similar to WAAS, LAAS corrects the standard GPS signal and enhances the accuracy of GPS to enable precision GLS approaches. However, LAAS transmits the corrected signal via a Very High Frequency (VHF) data link from ground stations near the airports it serves.[8] Although a separate service, the FAA intends for LAAS to compliment WAAS in providing precision navigation data in airport terminal areas and is part of the FAA and ICAO's move toward Performance Based Navigation.[9] Australia, Brazil, Germany, and Spain are working with the FAA to develop similar GBAS capabilities to enhance their airport terminal procedures.[10] Again, it is likely DoD officials could authorize military aircraft to use these systems under peacetime conditions, but may limit or restrict their use for security if they are located within a combat theater.

GPS Vulnerabilities

There are three broad categories of GPS threats and vulnerabilities: hostile actions, environmental hazards, or those that are self-induced by friendly action, or inaction, on the part of the US.

Hostile Intent

One of the most catastrophic threats to the GPS constellation is direct kinetic attack by a hostile nation or non-state entity looking to degrade the US military's precision strike and navigation capability. Identified by the "Rumsfeld Report" in 2001, nations "…hostile to the US possess, or can acquire on the global market, the means to deny, disrupt or destroy US space systems by attacking satellites in space, communications links to and from the ground or ground stations that command the satellites and process their data."[11]

Anti-Satellite (ASAT) missiles are the most precise form of attack against a GPS satellite. The Chinese test of a ground-based ASAT in January 2007 raised concern over the militarization of space. Although both the US and the former Soviet Union have tested ASAT missiles, no nation has conducted an ASAT test over twenty years. One US intelligence officer stated a test of this nature could possibly signal an end of twenty years of peaceful cooperation in space. China's demonstration of its ability and willingness to destroy satellites raises questions about the security of US space operations. Even though the missile targeted and destroyed a Chinese satellite, the resulting debris field endangered other satellites in low earth orbits as over 300,000 pieces of wreckage slowly spiral back into the earth's atmosphere.[12]

This too is a risk to US satellites. A kinetic attack weapon need not hit a satellite directly if instead it could place debris in or near the path of its orbiting target. Regardless, Michael Krepon, president emeritus of the Henry L. Stimson Center, stated in an interview that the Chinese test appeared to be a political statement challenging US superiority in space.[13] It is unlikely that the Chinese would openly attack the GPS constellation considering the international reliance on GPS for everything from civil air traffic navigation to precision timing for banking transactions. However, with the emergence of other GNSS, the protection of deterrence may lessen due to the availability of alternative navigation and timing sources should a potentially hostile nation attempt to degrade the US military's precision strike capability.

Directed energy weapons employed against individual or multiple satellites are another potential threat to US space-borne systems. These types of weapons overload the electronics onboard the target satellites in an attempt to temporarily or even permanently blind an electronic sensor or shutdown the satellite entirely. In September 2006, sensors in the Pacific traced attacks on US intelligence satellites to a ground-based laser complex in mainland China.[14]

The higher orbit altitudes used by the geosynchronous GPS constellation afford some protection from directed energy weapons. Although navigation satellites are still within reach, it would require significantly greater power to deliver an effective electronic attack. The directed energy would need to travel nearly fourteen times the distance and retain enough energy to affect the GPS constellation. Of more practicality and greater effectiveness would be the employment of an electro-magnetic pulse (EMP) weapon or even a nuclear detonation near one or more of the satellites.[15] Both China and Russia, as nuclear powers and spacefaring nations, have the capability of striking satellites or satellite orbits with nuclear weapons. However, the US and the international community would consider an attack of this magnitude an act of war and a violation of international space treaties.[16] At best, an EMP or nuclear detonation would make the affected GPS satellites temporarily unusable. At worst, it could destroy satellite circuitry, rendering the satellite uncontrollable, and potentially put it at risk of collision with other satellites. Taking the worst-case scenario one step further, the US GPS constellation is a carefully choreographed geosynchronous web that continually encircles the earth. The collision of two satellites in this orbital network might produce enough debris to impact other GPS satellites in a chain-reaction type sequence, causing much greater outages.[17]

In all likelihood, an overt attack by a nation in possession of kinetic or directed energy weapons such as Russia or China is low. Similarly, the deliberate targeting of the vast network of ground control stations or even augmentation facilities is equally unlikely. The US and international community consider such an attack an act of war and would likely lead to significant US retaliation.[18] Additionally, GPS satellites orbit at nearly 11,000 kilometers, much higher than potentially more tempting targets such as surveillance and reconnaissance platforms that orbit around 800 kilometers.[19] It is probable a hostile nation would focus such a level of effort on these closer-in platforms as targets for attack.

A terrorist organization would have difficulty obtaining the means to attack the GPS constellation directly. The ability to strike a satellite requires precision timing, high tech weaponry, and significant investment of capital. A terrorist network may have more success against a static target such as the ground control center, but with so many redundant sites and the ability for GPS satellites to continue functioning after contact is lost would render even a coordinated attack on multiple control centers little more than an expensive nuisance. Nonetheless, prudent planners should consider an attack on any space-based system a possibility.[20]

GPS jamming and spoofing receives much more attention than kinetic attacks as they are credible threats already encountered in operational theaters. Jamming is the intentional interference of electronic signals, like GPS, to deny their use.[21] Spoofing, in the case of GPS, is the purposeful transmission of a false signal to mislead a receiver into thinking it is in a location that it is not.[22]

Since the GPS signal is relatively low powered, a one-watt airborne jammer can deny the Standard Positioning Service (SPS) signal to an already locked on receiver at ten kilometers and prevent lock acquisition at a distance of eighty-five kilometers. A jammer at these ranges could conceivably block signal acquisition for all satellites down to the horizon. However, the effectiveness of the jammer is dependent on a number of factors: type of jamming signal, antenna pattern, geometry of the jammer, power output, and others. There are a number of these GPS jammers developed by nations unfriendly to the

US and available for sale on the open market. Russia, China, Iran, Cuba, and North Korea are all known to possess jamming technology.[23]

As an example, the Russian company Aviaconversia markets small, easily concealed jammers and routinely displays them at military hardware tradeshows.[24] The effectiveness of these types of jammers increases with quantity, whether airborne, carried aloft by aircraft or balloons, or deployed in masse on the ground to deny a wide area of coverage. These jammers can also be scaled to produce a much more powerful signal. A US GPS testing facility determined that many models available on the open market could be converted to megawatt-range GPS jammers.[25]

Spoofing of the GPS signal is far more difficult than jamming because an adversary is intending to covertly target and deceive a particular receiver without alerting the user to the attempt. However, spoofing can actually be far more effective at denying GPS. Spoofing cannot only introduce misleading signals in a localized area; the pseudorandom noise can actually produce a jamming affect to a far greater area.[26]

Due to its impact on the mission effectiveness of military aircraft, considerable effort has gone into creating mitigating technology to deal with the threat of jamming and spoofing. Systems such as the Precision Position Service (PPS), a new military GPS signal, commonly referred to as M-Code, and Selective Availability/Anti-Spoofing (SA/AS) have been developed to protect users. Aircraft such as those of the Iron Triad use these technologies to retain the ability to conduct their missions in a GPS denied environment.

The M-Code and SA/AS are all part of the transmitted signal for authorized or select US military, ally, and governmental agency GPS users. PPS is the term that specifically describes this level of GPS accuracy and integrity. Selective Availability (SA) refers to the intentional error previously broadcast along with the GPS civil code or C/A Code. This error was intentionally added to prevent adversaries from using the precision of GPS against the US. However, President William Clinton discontinued SA in May 2000. Even though the capability is still available, it has not been reinstated.[27] When a receiver with a properly loaded decryption code receives the civil signal, it is able remove the SA error. Additionally, this decryption also grants the user access to a highly precise second code transmitted by the satellites, also referred to as the P(Y) Code. The aircraft receiver then continuously compares the two signals to maintain accuracy and granting the Anti-Spoofing (AS) capability previously discussed. Vulnerabilities of the M-Code will be discussed later.

Relating this to the Rivet Joint in the opening scenario, the aircraft, using PPS, should have never drifted into North Korean airspace. However, PPS requires cryptographic keys to be loaded into the aircraft's GPS receivers. If they are not, the pilots of the Rivet Joint will not have any better accuracy than any standard civil user. Worst of all, the aircraft will not have adequate protection against spoofing or jamming. Human error can be a contributing factor in this case. In a hostile situation such as the scenario describes, the lack of these cryptographic keys could put the aircraft and crew at great risk.

Environmental Threats

The least controllable threat to the GPS constellation is the very environment in which it operates. Many believe space is an empty vacuum. However, space is actually one of the most brutal environments in which to deploy highly sensitive electronic devices.

Without detailing all of the various space weather phenomena, the space environment remains a constant threat to the satellites. Of most immediate concern is an increase in solar activity. The sun follows an 11-year cycle. An international panel of experts predicts the sun to reach its next Solar Maximum, a period of maximum solar activity, in May 2013.[28] Three significant space environment activities increase because of the Solar Maximum: solar wind, solar flares, and coronal mass ejections. An increase in solar wind brings with it gusts of ionized gases capable of pushing satellites off their orbits and an increase in geomagnetic storms.[29] System controllers can make corrections with onboard thrusters, but as there are no refueling procedures for the maneuvering thrusters on board satellites, this actually shortens their overall life span.[30] Increased solar flare activity on the sun ejects large doses of radiation across the electromagnetic spectrum. Once reaching the earth’s atmosphere, this causes increases in Sudden Ionosphere Disturbances disrupting satellite communications and potentially damaging electronics. Finally, Coronal Mass Ejections produce huge waves of energized particles and large electromagnetic storms capable of damaging the sensitive electronic equipment within the satellites.[31] In sum, the risks of a Solar Maximum are well known and relatively predictable.

Satellites launched over the last several decades have built in redundancies, electronics protection, and increased shielding against solar radiation. However, the GPS constellation is aging. Many of the GPS satellites have been operating well beyond their estimated mean vehicle life expectancy of 11.5 years. And, some are already operating on their backup or redundant systems.[32] Sixteen of the 30 satellites currently in use have been operating for greater than 10 years.[33] The increasing solar activity may cause higher than normal malfunction rates in the aging GPS satellites through signal degradation and electronics failure. Bombarded by radiation, highly-charged particles, and electromagnetic storms, these aged satellites may fail faster than expected. Unfortunately, fielding replacements for these satellites comprise part of the self-induced threat to the entire constellation.

Self-Induced Threats

Possibly the most significant risk to the GPS constellation is the delay of development, production, and launch of the follow-on GPS and augmentation satellites. There has long been identified the need to sustain and upgrade such a critical piece of infrastructure. The most recent GPS satellite replacement program, the research, development, and production of the IIF satellites, was plagued by problems and delays. Multiple contractor mergers, changes to program requirements, and lack of proper oversight all contributed to the repeated delays and cost overruns in fielding replacement satellites that were supposed to be in orbit in 2005.[34]

The first GPS IIF satellite is now scheduled to launch in December 2010 with another eleven projected to be launched over the next several years.[35] The follow-on program, GPS IIIA, is under an aggressive development and launch schedule that leaves very little room for delay. Unfortunately, given the life-cycle expectancy of the current constellation, the DoD suspects that many of the current satellites will reach the end of their operational life faster than they can be replenished. Based on GAO research, there is a significant risk that GPS coverage will drop below 24 operational satellites in the constellation, the number of satellites required for the GPS Operational System to be considered fully operationally capable.[36]

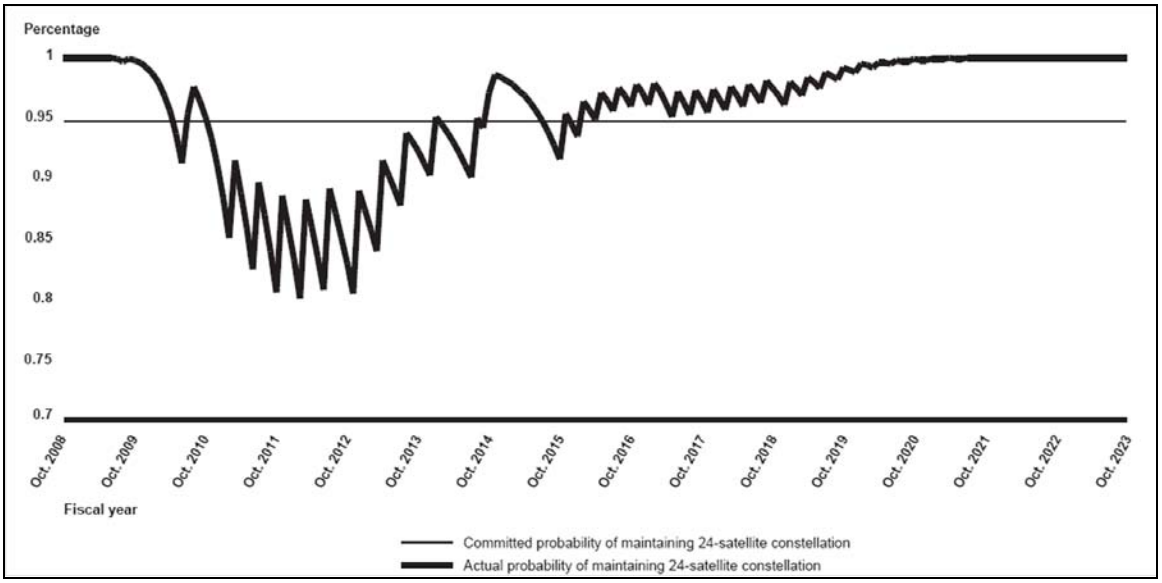

Figure 2. Probability of Maintaining a Constellation of at least 24 GPS Satellites based on Reliability Data and Launch Schedule as of March 2009

Source: United States Government Accountability Office, *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities* (Washington, DC: Government Printing Office, 2009), 20.

This data assumes the USAF will be able to keep the procurement and launch of the GPS IIF satellites on schedule and field the GPS III satellites according to its projected timetable. The GAO conducted an additional analysis of what delays to the GPS III program might mean to the constellation. A delay of even two years in production and launch would most likely result in a five-year period where the GPS constellation could drop below 24 satellites.[37]

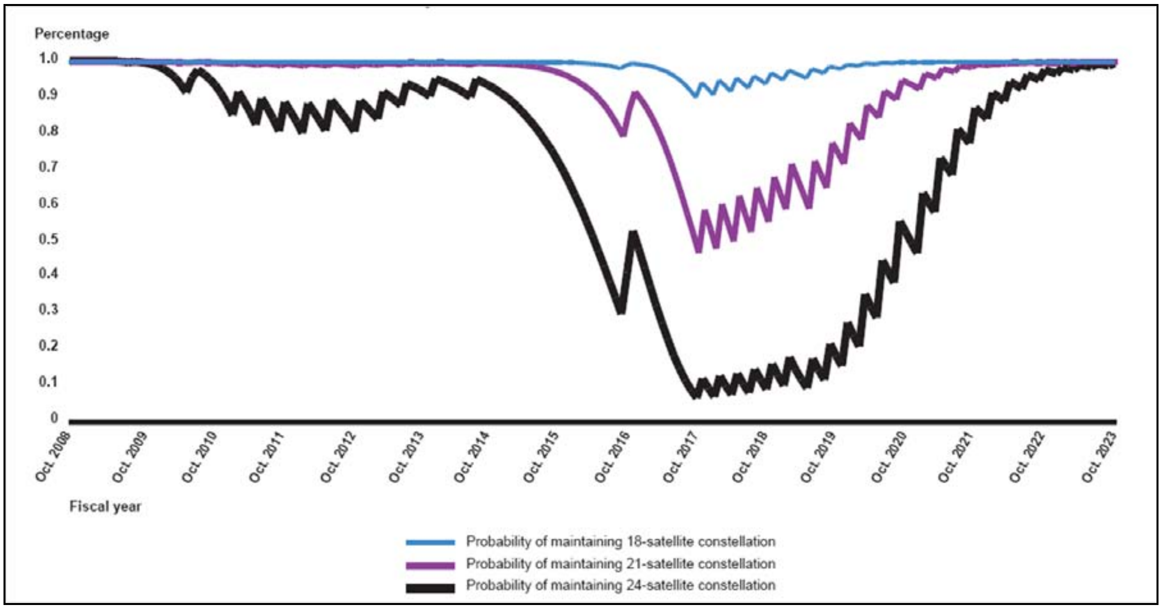

Figure 3. Probability of Maintaining a Constellation of at least 18, 21, and 24 GPS Satellites based on Reliability Data and Launch Schedule as of March 2009 and a 2-Year GPS III Launch Delay

Source: United States Government Accountability Office, *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities* (Washington, DC: Government Printing Office, 2009), 22.

If the GPS constellation drops below 24 operational satellites, the average civil user might notice a delay in GPS satellite reception or outages in the most severe instances. Air traffic controllers may have to reroute civil air traffic these outage areas. However, the military user would notice a significant difference. Precision guided munitions would lose the accuracy the military has come to expect. GPS outages may mean no coverage during transoceanic flights where military aircraft must travel to a contingency area by the quickest route. Operations close to a hostile border or airspace would require additional lateral separation to prevent inadvertent over-flight.[38]

What this means to US military aviation is there may be significant degradation to the availability, reliability, and integrity of GPS signals in the near future regardless of current mitigation efforts and protection protocols. Augmentation systems may help with the commercial air traffic, however, it will be of little help to US military aircraft operating in theater. These augmentation systems were designed to increase the precision of GPS signals at US airports, not worldwide.

Although primarily used for precision approaches to US airfields, WAAS has vulnerabilities of its own. Recently, Intelsat, one of the companies providing satellite services to the FAA, reported a serious technical issue in telemetry tracking and control of the satellite that broadcasts WAAS signals to the west coast of the US. Although the notification does not elaborate on the nature of the failure, the FAA states that WAAS users may experience service outages due to a lack of redundant signals.[39] Beyond its limited range of North American coverage, both WAAS and LAAS have the additional vulnerability of not being secured signals. As such, an adversary could still spoof or jam WAAS and LAAS signals since their signal architecture is openly available.[40]

One of the primary vulnerabilities for the user segment is the lack of military standard receivers capable of using augmentation and follow-on GPS technologies. None of the airframes in the Iron Triad currently has a WAAS/LAAS or GPS Mode-M capable receiver. Few multi-mode receivers are available for US military aircraft. GPS Mode-M capable receivers have not yet been fully developed to capitalize on the latest jamming and spoofing protection technology. Significant delays in development, production, and installation fleet-wide of these receivers will reduce the effectiveness of these upgrades and not allow military aviation to take advantage of the protections they give.[41] Modernization programs are focusing on these new technologies, but much of the needed equipment is still in research and development. Once fielded, completed modernization programs, such as Pacer CRAG, will have to be reinitiated or new upgrade programs contracted to integrate and install these new receivers.

Unfortunately, the integration of GPS into nearly every aspect of the US military creates an additional vulnerability–overreliance. What this means to the aviation community, and the Iron Triad in particular, is that modernization efforts to improve navigation capability and comply with CNS/ATM requirements cannot wholly depend on the precision and reliability expected from GPS. Adversaries may place greater emphasis on denying GPS to US air and ground forces alike. Systems designed to meet civil air traffic requirements will not provide protection against an opponent with the skill to disrupt GPS signals. The US must make efforts to ensure GPS protection and backup navigation measures are in place onboard Iron Triad aircraft well before the US engages such an enemy.

CNS/ATM Requirements

The vulnerabilities of GPS are of critical importance when considering the CNS/ATM requirements enacted for safety-of-flight in international airspace. GPS plays a significant role in the ICAO strategic plan for air traffic management. These new standards evolved from the findings of the Special Committee on Future Air Navigation Systems commissioned by ICAO in 1983 when it determined the systems and support structures for handling civil air traffic had reached their limits. Initially known as the simply the FANS concept, CNS/ATM has evolved to include requiring aircraft to install automated, interrelated technologies that utilize satellite based technology.[42]

Communications

Under CNS/ATM, new communications requirements are broken down into two basic categories, data link communications and decreased VHF channel spacing. Data link communications include the use of beyond line of sight (BLOS) technologies such as satellite communications (SATCOM) data link and High Frequency Data Link (HFDL) to contact pilots in oceanic airspace. For routine, non-time critical message traffic between aircraft and ground control agencies, Controller Pilot Data Link Communications (CPDLC) sets are also required. In heavily congested airspace, such as Europe, controlling agencies attempt to talk to aircraft on standard VHF frequencies. However, with so many agencies in close proximity, transmission bleed-over from widely broadcasting radios hampered communication and put crews and passengers at risk. Flight through European airspace now requires a VHF radio capable of discriminating and isolating radio frequencies down to 8.33 kilohertz (kHz) of separation to prevent bleed-over.[43]

Navigation

Navigation requirements for CNS/ATM fall under the title of Performance Based Navigation (PBN). PBN defines performance requirements for the navigational avionics of aircraft and outlines requirements for airspace and air route access.[44] PBN consists of three major components: Area Navigation (RNAV), Required Navigational Performance (RNP), and Vertical Navigation (VNAV).

RNAV is the capability of an aircraft avionics system to maintain a course within the limits of a terrestrial ground navigation aid or a self-contained navigation system.[45] Basically, it is the ability to follow the centerline of a course straying no further than the acceptable precision limits of the navigation aid that is being used, such as a Tactical Air Navigation aid (TACAN), GPS, or an Inertial Navigation Unit (INU) onboard the aircraft. However, RNAV does not require performance monitoring or alerting on the navigation system. For certain airspace or air routes, a minimum RNAV capability is given for each route. For example, RNAV-2 requires an aircraft have equipment capable of keeping it two nautical miles left or right of course over 95% of the time while flying on that particular route. Applicable avionics for RNAV include a Flight Management System (FMS) that integrates various elements of an avionics suite, scanning Distance Measuring Equipment (DME) to receive accurate distance information from transmitting sources, GPS, or an Inertial Navigation System (INS). A combination of this equipment is required for access into RNAV routing or airspace.

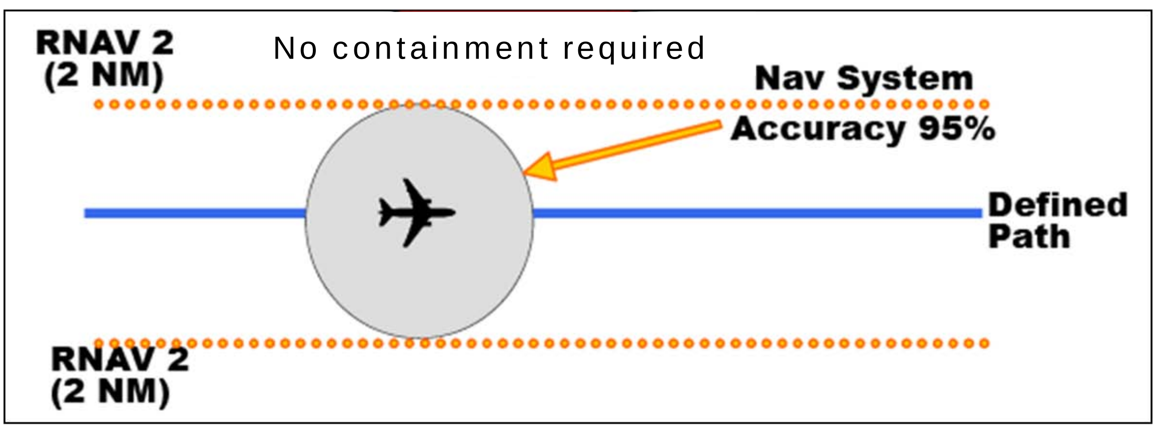

Figure 4. RNAV Requirement Definition
Source: Roger Francis, *CNS/ATM Navigation 101* (Briefing given at the AFCEA CNS/ATM Conference, San Antonio, TX, 2010), Slide 12, http://www.afceaboston.com/documents/events/cnsatm2010/Briefs/1%20-%20Tuesday/02%20Navigation101%20(Roger%20Francis).pdf (accessed 12 May 2010).

RNP requirements for aircraft include all the same RNAV requirements plus the ability to monitor performance and alert aircrew of degradation of the navigation equipment onboard the aircraft. Receiver Autonomous Integrity Monitoring (RAIM) is a recently added software solution to meet the monitoring and crew alert requirement. RAIM continually checks the accuracy of one satellite position information against the others signals tracked by the GPS receiver. In addition, the aircraft avionics must be able to conduct route containment and integrity. In more common terms, the aircraft must have the ability to stay within two times the width of the defined RNP route regardless of degradation. For example, on an RNP 2 route, an aircraft must remain inside a four nautical mile left and right of course containment corridor.

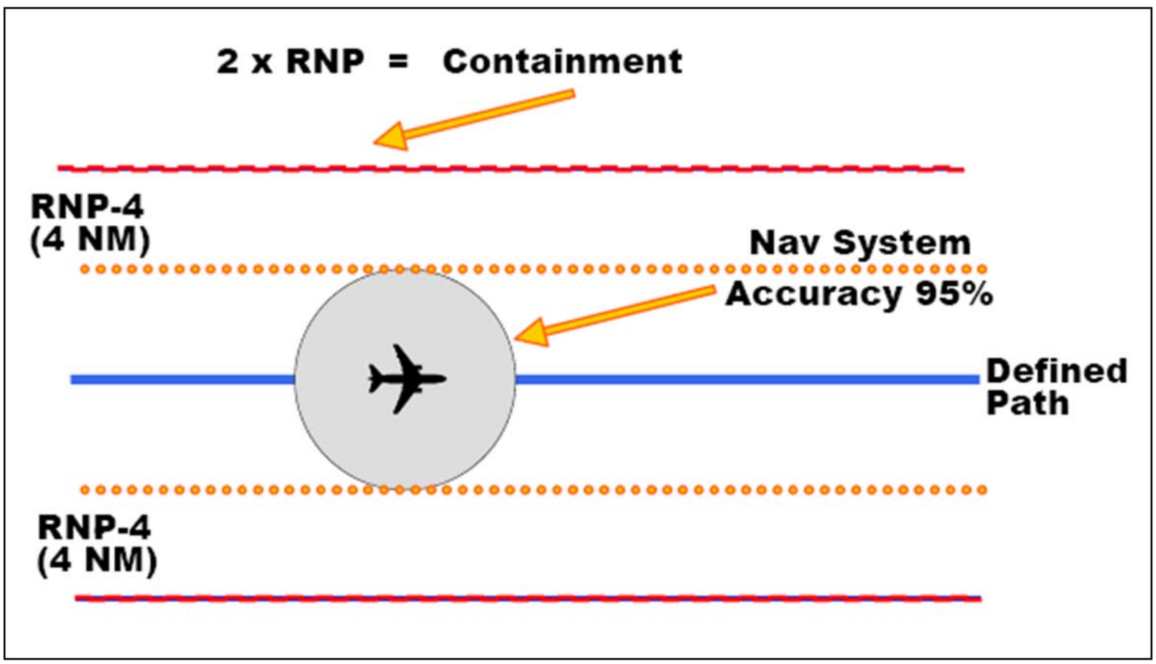

Figure 5. RNP Requirement Definition
Source: Roger Francis, *CNS/ATM Navigation 101* (Briefing given at the AFCEA CNS/ATM Conference, San Antonio, TX, 2010), Slide 17, http://www.afceaboston.com/documents/events/cnsatm2010/Briefs/1%20-%20Tuesday/02%20Navigation101%20(Roger%20Francis).pdf (accessed 12 May 2010).

The aircraft must also be able to meet the RNP requirements for defined routes. For oceanic routes such as the North Atlantic Tracks, an aircraft must meet the RNP required performance as well as specific communications and surveillance capabilities in order to gain access. In the coming years, ICAO, the FAA, and EUROCONTROL will increase the RNP performance requirements. In order to fly routes in the continental US, aircraft must currently meet RNP 2, containment four nautical miles left or right of course, requirements. As soon as 2014, those requirements, as well as routes through European airspace, will increase to RNP 1. Terminal procedures, flight in and around the terminal airspace of airports, require RNP 1 and are scheduled to increase to RNP 0.3 around 2014 as well.[46]

Without overtly stating GPS or a GNSS capable navigation system is required, ICAO, the FAA, and EUROCONTROL requirements for navigational performance dictate the use of a GNSS navigation system as that is the only system currently capable of that level of navigation precision. In essence, GPS is now accepted as the primary navigation source for aircraft. Unfortunately, industry has based most of their modern avionics suites on GNSS capable navigation systems only and removed or relegated most other forms of navigation capabilities to the role of redundancies or backup systems. In particular, passenger aircraft now use Inertial Reference Units (IRU) instead of INUs.[47] What this means is that GPS drives navigation and the IRU provides aircraft systems with attitude and position if GPS is providing initial position information. If there is no GPS signal, an IRU cannot take over navigation.

Surveillance

The surveillance piece of the CNS/ATM requirements model consists of an aircraft's ability to self report its position to both ground control agencies and other aircraft. Aircraft are required to have Mode-S identification transmitters and receivers and a Traffic Collision Avoidance System (TCAS) and will soon be required to have Automatic Dependent Surveillance-Broadcast (ADS-B) systems to access international airspace. Mode-S is a signal transmitted along with other aircraft identification transmissions. However, Mode-S enables TCAS to display and predict potential aircraft collisions, a critical safety capability in areas of increasing air traffic. ADS-B automatically transmits an aircraft's flight information and integrates that information into the FAA's Next-Generation Air Transport System, enabling flight controllers and flight control centers to manage air traffic more efficiently.[48]

Because CNS/ATM requirements are increasing, previous upgrades to USAF aircraft will become insufficient. The Rivet Joint fleet, previously part of the KC-135 Pacer CRAG modification, will have to again be updated to meet these new requirements. Upgrade programs like DRAGON have already had to adjust contractor requirements to ensure compliance and prevent a second round of modernization.

Navigation Requirements of the Iron Triad

The navigation requirements of the Iron Triad aircraft are more stringent than just meeting specification for flights through international airspace. The nature of the missions conducted by each airframe require precision placement of each platform's sensors. In many cases, the aircraft must be positioned right at the very edge of an airspace boundary and is continuously monitored to avoid inadvertently flying into restricted or no-fly airspace. Currently, navigators perform the job of precise monitoring and correction of flight paths. But navigators are not used on all large USAF airframes.

Even before advances in avionics made GPS a viable system for aviation, aircraft like the KC-10 Extender did not have a navigator as part of the flight crew. The Extender's two pilots, typically supporting aerial refueling missions, maintained the aircraft's navigation suite of three INUs, keeping it on course and on time. These are important missions, the very backbone of America's ability to rapidly deploy forces throughout the world. But the KC-10 and the KC-135's mission are different than that of the Iron Triad. Aerial refueling is essentially done in isolation and, in most cases, could still be executed even if their new GPS aided navigation suites should fail. But the Iron Triad relies on GPS for both aircraft navigation and to drive the accuracy of the mission equipment onboard.

The radar mapping overlays on both the JSTARS and AWACS use own-ship position information to identify the coordinates of tracks. Without the navigation suite's precision position information being fed into the mission computer, the symbology displayed on the mission terminals would simply be radar returns with no positional information to vector aircraft or ground forces for intercept. Without precision position information, the Rivet Joint would not have the ability to triangulate the position of the signals it intercepts and interrogates.

An additional component critical to air battle management is the role each of the Iron Triad aircraft plays in creating and maintaining the air picture. Initially, Joint Tactical Information Distribution System (JTIDS) Class 2 Terminals were installed on all AWACS, and later JSTARS and Rivet Joint aircraft.[49] JTIDS, also known as Link 16, provides near real-time combat information in data link architecture. When one of the Iron Triad aircraft is on station, it acts as a type of airborne hub for the JTIDS data link network. Other aircraft join the data link and can share data from their own onboard systems as well as receive a complete air picture. This data is also transmitted down to ground terminals enabling control facilities, such as the Air Operations Center (AOC) to track and make inputs to the air battle.

Prior to GPS upgrades on each of these aircraft, the Iron Triad used highly accurate INUs. However, these older generation INUs could not meet the precision navigation requirements of the FANS concept. In anticipation of the more stringent navigation requirements, the fleet was upgraded to its present-day navigation equipment. Currently, the JSTARS and AWACS aircraft use dual Northrop Grumman LN-100G Embedded GPS/INU units and a qualified navigator. The Rivet Joint now employs a similar system but incorporates a stellar tracker. The Northrop Grumman LN-120G utilizes a highly accurate INU augmented and updated by a state-of-the-art stellar telescope that tracks stars day or night. GPS assists the stellar tracker in stellar acquisition and aids in position resolution. However, the system is capable of one-half nautical mile navigation precision without a GPS signal for up to 18 hours.[50] This allows the Rivet Joint to remain on-station even in a GPS denial environment. Again, as with the other Triad aircraft, the Rivet Joint uses a navigator to operate and maintain the navigation suite.

Navigators onboard Iron Triad aircraft perform a vast array of duties. Prior to flight, they plan all aspects of the mission including route, orbit location, aerial refueling, and alternate landing locations. They often complete in-flight re-planning to accommodate mission changes or contingency operations. They monitor and update the navigation suite and provide redundancy by performing dead-reckoning navigation to return a severely degraded aircraft to base safely. Finally, they provide an additional airminded aircrew member during complex, high-intensity missions when task saturation becomes a risk.[51]

The aircraft that make up the Iron Triad rely heavily on the precision of their navigation solutions to execute their mission. Although each aircraft uses a PPS GPS navigation solution, the vulnerabilities of GPS put that mission at risk should future upgrades rely too exclusively on GPS. With the replacement and sustainment of the GPS constellation in question, the aircraft must ensure they have adequate backup navigation systems onboard to maintain mission effectiveness. Aircraft modernization programs must retain the ability for any of the Iron Triad aircraft to operate in a GPS degraded or denied environment.

Modernization Programs

The DRAGON modernization is joint program to upgrade both US and NATO E-3 Sentry aircraft solves two critical shortfalls within the fleets. The first addresses replacement issues as the parts that make up the avionics suite, called Line Replaceable Units (LRU), become obsolete. The second element involves the upgrading avionics to comply with the forthcoming CNS/ATM requirements for access in US, European, and international airspace.

Avionics manufacturers will soon stop producing many of the LRUs used by the avionics suite in the E-3. As the stockpiles of available new LRUs dwindle, additional problems arise as repair facilities stop refurbishing existing units due to lack of replacement parts. The E-3 System Program Office, the organization charged with sustainment of the E-3, had only two choices. The first was to attempt to find a vendor who could reverse engineer repair parts or attempt to replace existing electronics with new digital internal components. However, this option would create a greater sustainability problem as the replacement components would then become highly customized and limited in supply. Additionally, this option would not have meet future CNS/ATM equipment requirements as the original avionics suite lacked many of the required integrated systems. The second option involved the complete replacement of existing components and modernization the entire cockpit with a commercial off-the-shelf (COTS) avionics suite. By opting for a COTS replacement program, the E-3 can take advantage of standing stocks of commercially available components and preexisting logistical lines of support. Software changes could accommodate most of the military specific requirements for mission execution, but not all.[52]

The cockpit and avionics of an E-3, a modified Boeing 707 airframe, are not all that different from that of a Boeing 737. With a few modifications, Boeing, the prime contractor for the DRAGON program, proposed to strip out the analog components of the E-3 cockpit and replace it with a modernized digital avionics suite similar to the current Boeing 737 suite. This included removing the navigator station and replacement of the primary navigation components with primary GPS navigation system coupled to IRUs for attitude and flight data information. The existing navigation system consists of a pair of Embedded GPS/INU (EGI) LRUs. When questioned about redundancy, the Boeing engineers stated that there would be two GPS coupled IRUs, one as a backup for the other.[53] However, given the mission areas and proximity to potentially hostile territories, the redundancy of an independent, self-contained navigation system like the INU must be retained in the event the aircraft experiences a GPS degraded or denied environment. In an environment like the one in the opening scenario, reliance on an IRU as a backup source would have simply kept the aircraft on an assigned heading, not a desired course. It would have only taken a few minutes to cross into North Korean airspace.

Iron Triad aircraft can become non-mission capable without a reliable backup navigation source for mission computer system. NATO has so far opted to eliminate the navigator position from the new cockpit modification. However, the US will upgrade the Navigator Flight Station and retain the navigator in acknowledgement of the complex nature of the AWACS mission. Research done prior to the KC-135 Pacer CRAG cockpit modernization stated that members of the Air National Guard had reservations about replacing manpower with technology. Their primary concern was with a complex wartime mission and the duty of managing many airplanes in a small airspace, a three-person crew would become task saturated.[54] Avionics updates for all the Iron Triad platforms must consider this unique mission-specific contingency. To downplay the need for navigation redundancy is to degrade the mission effectiveness of the Iron Triad in a peacetime or combat environment.

GPS vulnerabilities, in particular the sustainment and upgrade risks associated with the satellite constellation, can be significant factors regarding Iron Triad mission effectiveness. The CNS/ATM navigational requirements driving modernization of the Iron Triad aircraft and the heavy reliance on GPS to meet those requirements must be considered in current and future navigation programs. The specific navigation requirements of the Iron Triad preclude using commercial airliner equivalent avionics suites because of the potential to jeopardize mission accomplishment and flight safety concerns. Finally, the DRAGON modernization program and previous upgrade programs provide some insight into future guidance. The next chapter offers conclusions and makes recommendations for future programs and research.

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CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This thesis has explored the vulnerabilities of and threats to GPS and their impact on the USAF C2ISR fleet known as the Iron Triad. From careful study of the research material, the evidence suggests that overreliance on GPS as the primary method of navigation for the Iron Triad aircraft could jeopardize mission effectiveness under certain circumstances.

Conclusions

GPS is a robust and time-tested system. In spite of credible threats and potential attack by hostile nations or non-state organizations, considerable safeguards are in place to ensure its continued reliability and availability for both civil and military users alike. Although the DoD should not dismiss the possibility, the probability of an attack on any GPS segment is extremely low.[1] However, the GPS constellation is an aging system. The USAF has built and scheduled the launch of the GPS Block IIF satellites. The GAO report on sustainability states even this may not be enough to keep 24 satellites on orbit and operational should they not exceed their designed operational life.[2] Additionally, the scheduled progress of the GPS Block III satellite replenishment program remains in question. The GAO report states the US military should take steps to prepare for operations with a smaller GPS constellation and recommends changes in its approach to mission planning, operations and tactics.[3]

The mitigation procedures in place for civil aviation consist of a robust augmentation system. Both ground and space based, these systems will provide much higher precision during critical phases of flight, take-off and landing. However, these augmentation systems are highly localized and only provide improved accuracy around airports. Additionally, none of these systems use protected encryption to defend against jamming or spoofing. Regardless, the Iron Triad operates in areas where US augmentation systems are unavailable or too far out of range to be effective. In the event the Iron Triad aircraft would be in range of another nation's DGPS, its use then becomes a question of trust in the nation providing the augmentation service and trust that the unprotected signals are not being jammed or spoofed.

The mitigation specifically created for the military is still in development. As stated, only eight satellites currently have the capability of transmitting the M-Code. M-Code should achieve initial operational capability of eighteen satellites with the successful launch and check out of the tenth GPS IIF satellite scheduled for 2013.[4] However, according to the GAO report, the development and production of military receivers capable of using the protection offered by M-Code is still significantly behind schedule. Additionally, any delay to the development and deployment of the Block III GPS satellites puts the constellation at risk of falling well below the requisite 24-satellite requirement to be considered fully operationally capable. The possibility exists that current satellites will remain in service longer than there designed life cycle, but there is not data currently available to indicate that the satellites' life expectancy is overly conservative.[5]

The navigation requirements of the Iron Triad fleet exceed those of the average civil air carrier. It is not that they necessarily require greater position precision, but that the Iron Triad fleet is expected to operate for hours in airspace where the possibility of

GPS denial is much greater. Additionally, because the sensors on board the Iron Triad aircraft rely on precision navigation to meet mission requirements, the navigation suites on board each aircraft must be reliable, robust, and have redundancy to continue their missions to provide dynamic command, control, intelligence, surveillance, reconnaissance, and battle management. Current navigation systems on the Iron Triad fleets do not meet CNS/ATM requirements. The USAF must continue efforts to comply with these mandates in order to ensure aircraft of the Triad fleet can gain access to optimized airspace and air routes worldwide. Although the modernization programs like DRAGON are working to achieve compliance by integrating GPS as a primary navigation source, the USAF must ensure redundancies are in place. Relying too greatly on civil advancement in GPS augmentation or other nations' GNSS places the US military at too great a risk and leaves military aircraft susceptible to the jamming and spoofing of unsecured systems.

Based on the conclusions drawn from the research presented in this thesis, the following recommendations are suggested for the USAF and DoD.

Recommendations

1. Long-Term: The USAF will have to maintain strict control over the GPS III satellite development, launch, and operation to ensure there is not a significant reduction in GPS worldwide coverage. Consistent with the recommendations of the GAO study, an appointed authority to oversee and a program office to administer the development program ensures program changes are controlled, requirement modifications are minimized, and milestones are met. This has the added benefit of keeping the US GPS constellation competitive with other countries aggressively pursuing GNSS programs.

Failure to maintain the tight schedule proposed by the USAF for development, production, and launch of the GPS III replacement program puts the full operational capability of the GPS constellation and updated PPS security for the military at risk.

2. Mid-Term: The USAF should consider placing an additional crewmember on the flight crews of these aircraft to ensure navigation systems are properly monitored and maintained. With the potential for the GPS constellation to drop below full operational capability, the addition of another airminded crewmember would mitigate the impact of GPS degradation. In the event of a GPS outage, it is possible for two pilots to become task saturated.[6] Modern automated avionics suites rely on GPS to manage flight paths. In the Iron Triad aircraft, the navigation system is critical to the mission sensor equipment. The additional crewmembers must be capable of operating on-board backup navigation systems and providing a level of precision navigation for the aircraft to remain on-station. Additionally, backup navigation equipment used as a primary navigation source requires close monitoring to ensure accuracy does not drop below the quality and precision required to effectively operate the mission equipment. These additional aircrew should be retained at least through 2022, the potential risk period of GPS satellite loss projected by the GAO estimates. In order to achieve this capability, the USAF could train pilots or flight engineers to operate these systems or simply retain navigators already integrated into these flight crews, whichever provides the greatest capability at a reasonable cost. The USAF should consider conducting research to study the most effective method of providing additional flight crew to meet redundancy requirements on-board Iron Triad aircraft.

3. Short-Term: The USAF must focus on the development and production of multi-mode GPS receivers capable of using GPS Mode-M, Galileo, and WAAS and LAAS signals, and compatibility with other nations' GNSS and DGPS services in order to meet current and future CNS/ATM mandates. Commercial off-the-shelf components may not be adequate as USAF military aircraft still require the ability to decrypt the military GPS signal. Delays to acquiring these receivers will limit the capabilities of aircraft navigation systems, possibly force denial of optimized airspace, and increase vulnerabilities to DoD aircraft. However, the USAF must not modernize aircraft at the expense of alternate backup navigation sources. The USAF must retain systems such as the LN-120G Stellar-Inertial Navigation System on board the Rivet Joint and potentially install them on both the JSTARS and AWACS platforms to ensure these aircraft can remain on-station and fulfill their missions even in the event of GPS denial or degradation.

In addition to these recommendations, the USAF should conduct a study analyzing the benefits of retaining the navigator on board special mission aircraft such as those of the Iron Triad. All of these airframes carry electronic intelligence gathering equipment. Navigators with additional training operate these electronic systems. On board various aircraft, they have been called Electronic Warfare Officers (EWO) or Weapons Systems Officers (WSO). For example, EWOs conduct analysis of electronic signals gathered by systems on board the Rivet Joint.[7] Yet all of these officers have completed navigator training. The USAF has recently combined the curriculum for these specialized navigator tracks. Now designated as Combat Systems Officers (CSO), all navigators receive identical training in aircraft navigation and electronic signals analysis.[8]

By integrating the navigator position with that of the electronic analyst on all of the Iron Triad airframes, the USAF could capitalize on retaining the navigator skill set should the need arise. Air Force leadership could meet quickly enhance current flight crew capabilities by tapping into an already trained pool of aviators.

The conclusions indicate a significant risk to the GPS constellation. Although mitigation procedures are in place to lessen the effects on civil aircraft, there is still potential for mission effectiveness degradation. The USAF should seriously consider the recommendations for modernization programs of both US C2ISR aircraft and the NAVSTAR GPS. Finally, the Air Force must address the need for adequate redundancies to ensure Iron Triad aircraft meet safety-of-flight requirements and retain mission effectiveness in a GPS denial environment.

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[1]Commission to Address United States National Security Space Management and Organization, *Report of the Commission to Address United States National Security Space Management and Organization* (Washington, DC: Government Printing Office, 2001), viii.

[2]United States Government Accountability Office, *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities* (Washington, DC: Government Printing Office, 2009), 19.

[3]Ibid., 25.

[4]Ibid., 27.

[5]Ibid., 21.

[6]John E. Ehrhart et al., *KC-135 Cockpit Modernization Study and Crew Reduction Feasibility Demonstration* (Wright-Patterson AFB, OH: Government Printing Office, 1992), 27.

[7]Collins, James M. and Joseph S. Tartell, *United States Air Force Occupational Report: Navigator Utilization Field* (Randolph AFB, TX: Government Printing Office, 1999), 7.

[8]Otto Kreisher, “Versatile, Ready, and Rated,” *Air Force Magazine* (August 2007), 60.

GLOSSARY

Airminded. A term commonly used in aviation to indicate an individual who is familiar with the flight environment or has had some form of flight training, for example pilots, navigators, flight engineers, or aerial observers.

Glass Cockpit. The term commonly used to describe aircraft outfitted with large liquid crystal displays (LCD) to display critical navigational, aircraft system, and weather information to the pilots in place of analog gauges.

International Airspace. The airspace concurrent and above the internationally recognized "territorial waters" as outlined by maritime law.

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